26837 DUP

IGM87TC-203-507-G
CNRC 26837

THE INFLUENCE OF THICKNESS ON THE FATIGUE ENDURANCE OF NON-LOAD CARRYING SPOT WELDED JOINTS

F.G. Hamel and J. Masounave

Industrial Materials Research Institute
National Research Council Canada
75 De Mortagne Blvd.
Boucherville (Quebec) Canada J4B 6Y4

ABSTRACT

Non-load carrying spot welded joints of 301L stainless steel sheets were tested in fatigue. Different combinations of 1.5, 3 and 4.5 mm thick sheets were evaluated. The initiation of the fatigue crack was detected by a compliance method. The obtained S-N curves revealed that the presence of a non-load carrying connection considerably reduces the fatigue limit as compared to plain specimens. It is also shown that the fatigue limit decreases when the thickness of the non-load carrying sheet is increased. However, the thickness of the load carrying sheet has little influence when the data are compared in function of the stress in this sheet. The comparison with other results also showed that the alloy has a small influence on the high-cycle regime.

These results indicate that for design purpose in fatigue, the load carried by a spot welded connection is not the only factor to consider. More specifically, in the case of a low-load carrying joint the stress in each sheet and the thickness of the sheet attached to it are the controlling factors in high-cycle fatigue.

KEYWORDS

Fatigue; spot welds; thickness; endurance limit; non-load carrying; stainless steel; resistance welding.

INTRODUCTION

Spot welded joints are extensively used for the assembly of sheet metal structure especially in the transportation industry. For thin sheets, the diameter and spacing of the welds can be designed such that multi spot assemblies can carry a static load comparable to the static strength of the sheets.

However, the situation is different for the fatigue resistance especially in the high-cycle regime. Spot welded joints are severe stress concentrators and can even be considered as crack-like defects. The fatigue crack initiation period is almost non-existant and most of the fatigue life is in the crack

growth region (Davidson, 1983a; Pollard, 1974; Overbeeke, 1974). The situation is more critical for high strength alloys (stainless steels and HSLA steels) because their fatigue properties are not improved as much as their strength. In fact, the fatigue crack growth properties of HSLA steels are similar to mild steel and are inferior for austenitic stainless steel. It follows that the high-cycle fatigue endurance of spot welded joints of high strength alloys is of greater concern than for plain carbon steel because structures made of sheets of high strength alloys are usually more stressed. Moreover, the quality control tests used in the industry (peel, tensile shear and cross tension) which are adequate to characterize the static strength of a spot welded joint show a poor correlation with the high-cycle fatigue endurance (Davidson, 1983a).

In consideration of these facts, the fatigue behaviour or resistance spot welded joints has been extensively studied by many investigators (Davidson, 1983b, 1983c, 1984; Iwasaki, 1983; Orts, 1981; Overbeeke, 1984; Pollard, 1984; Pook 1975; Rivett, 1983; Wang, 1985). Review papers have also been published by Davidson (1983a) and Defourny (1985). Most of these studies have been performed on single or multi spot joints in the single lap shear configuration. In this configuration, 100% of the stress in the sheets is caused by the load transmitted through the spot weld and these joints can be designated fully load carrying.

Fully load carrying joints are not representative of many practical situations. The other extreme is the non-load carrying joint in which a short sheet is spot welded on a longer sheet (Fig. 1). Only the longer sheet is stressed and the smaller one acts as a stiffener producing a stress concentration area in the long stressed sheet. Very few studies (Defourny, 1981, 1985;

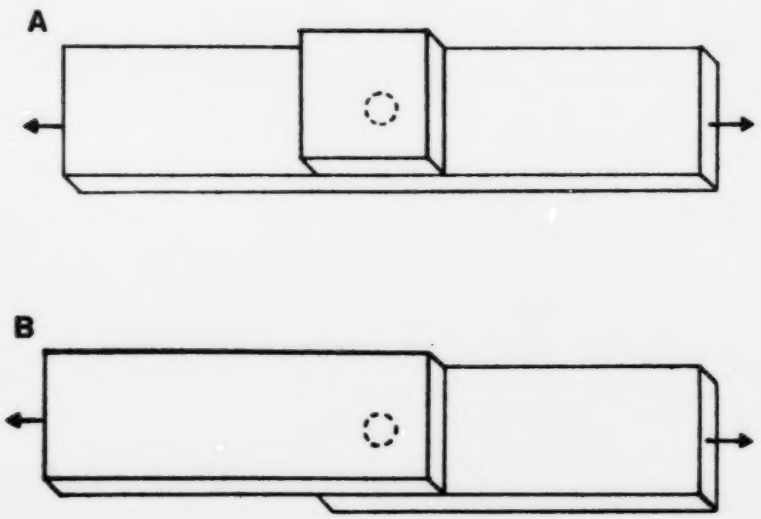

Fig. 1 Schematic illustration of a) non-load carrying spot welded joint and b) fully load carrying spot welded joint.

Sperle, 1984) on the non-load carrying configuration were reported in the literature.

Defourny (1981, 1985) obtained load vs number of cycle curves of non-load carrying samples of 1 mm thick sheets. They compared these results to 100% load carrying configurations including the single lap shear joint. They concluded that the fatigue resistance for a non-load carrying spot corresponds roughly to the performance of the plain base material. They outlined the importance of the notch effect in the load carrying configurations.

Sperle (1984) performed similar tests on 1.2 mm thick non-load carrying samples. Fatigue crack initiation in his specimens occured in the base metal for single spot weld. In the case of samples with 3 spot welds in a row, the fatigue strength was found to be slightly lower than for plain specimens. He concluded that "spot welded attachments can, if necessary, be placed on strength members without being detrimental to the fatigue behaviour of the structure of which they form a part". In a recent investigation (Hamel, 1987) with 2 mm thick non-load carrying joints, it was shown that these joints were significantly reducing the fatigue limit. It was also concluded that these results might be an indication that the effect of non-load carrying attachments is increasing with the thickness.

EXPERIMENTAL PROCEDURES

The fatigue samples for the present investigation were fabricated from 301L/MT stainless steel. The mechanical properties and chemical composition of 301L/MT as provided by the alloy manufacturers are given in Table 1. The nugget diameters are given in Table 2. In this table like in the following of the text, the thickness is designated by two numbers where the first is the thickness of the short sheet and the second the base sheet. The width of the samples was 50 mm and the free length (between the grips) 195 mm.

Additional fatigue tests were also done with holed samples of the same material as a comparison. These samples had a 6.35 mm drilled hole in 3 mm thick, 47 mm wide plates. Most of the fatigue tests were performed on a 100 kN axial servo-hydraulic machine in load control mode. A 250 kN machine was used for some of the tests at higher loads. Many of the tests were performed under computer control. This eliminated the need of readjustig the control single during the test providing a more constant load amplitude. All the tests were done at a load ratio R of 0. The tests are run until complete separation of the samples.

For every test, an extensometer was attached across the nugget on the stressed sheet side. The signal of the extensometer is used to monitor the compliance change during the test and to provide an early indication of crack initiation and to indicate when the crack reaches the opposite face of the sheet. The procedure is explained in details in a previous reference (Hamel, 1987) and is based on the presence of a minimum in the compliance vs number of cycles curve.

RESULTS AND DISCUSSION

The results of the fatigue tests are plotted on Fig. 2 to 5 for the non-load carrying joints and on Fig. 6 for the holed samples. On these curves the stress range (equal to S_{max} for R = 0) is plotted versus the number of cycles for initiation and fracture. It should be noticed that the criteria used to determine the "initiation" does not correspond to the nucleation of a small microscopic crack but to the moment when the thumbnail crack almost reaches the outside face of the sheet.

TABLE 1 Mechanical Properties and Chemical Composition of 301L MT

a) Mechanical Properties

t (mm)	σ_y (.2% offset) (MPa)	σ_{UTS} (MPa)	elongation %
2	573	920	32.8
4.5	613	951	31.8

b) Chemical Composition

C	Si	Mn	P	S	Ni	Cr
.030	1.00	2.00	.040	.020	6.5-8.8	17.0-18.0

TABLE 2 Spot Diameters

t_b/t_s (mm)	spot diameters(mm)	
	required	measured
1.5/1.5	5.6	7.6
3/3	7.6	9.5
4.5/4.5	8.9	9.2
1.5/4.5	5.6	7.0

1.5/1.5 mm Samples

On Fig. 2, the endurance limit is not defined accurately and is indicated by a hatched area. Filled symbols at low stress correspond to samples from a different batch than those represented by open symbols. It was noticed that the indentation of the nugget of these samples had a different shape due to a different electrode (hemispherical rather than truncated cone). The overall thickness at the center of the spot was slightly larger (2.92 ±.01 vs 2.85 ±.04 mm) in spite of a deeper indentation (.108 ±.02 vs .064 ±.008 mm). The initial normalized compliance of these samples was also slightly smaller than for the other specimens (.975 ±.03 vs 1.02 ±.01 mm). This observation agree with previous data (Hamel, 1987) where higher compliance was correlated with higher endurance and where higher compliance was attributed to nuggets with large porosities, of smaller diameter or deeper indentation. It is then clear that the fact these specimens were from a different batch affected the data. On the other handfit is not completely clear which factor in the nugget geometry influenced the most the results. The additional tests with the new batch of samples were performed to confirm the determination of the fatigue limit based on a single specimen since it was known from other tests that a

false fatigue limit might be caused by a specimen slightly overloaded during testing. Obviously, the new batch of samples didn't improve this aspect of the data.

One sample ($2x10^6$ cycles, 273 MPa on Fig. 2) exhibited a markedly higher endurance than the other samples. Post failure examination indicated that cutting fluid had pengtrated between the two sheets before testing. The fatigue endurance improvement caused by oil has already been noticed by Overbeeke (1974).

Two samples (indicated by triangles) tested at high stress failed outside the gauge length due to cracks initiated on the edge of the sample. Large plastic deformation around the weld nugget of these samples reduce the efficient stress intensity factor in this area and can promote fatigue initiation at the edge of the samples. These edges are sheared which leaves a rough finish and strain hardened material. In fact, many small cracks were observed along the edges. A third sample also failed outside the nugget area at a stress of about 220 MPa. This is much more amazing and no explanation can be found for it. However, post failure fractographic examination revealed fatigue crack initiation at the expected location on the nugget periphery.

3/3 and 4.5/4.5 mm Samples

On Fig. 3 and 4, the endurance is much better defined than for Fig. 2. All the failures occured in the nugget area and no cracks in the machined (milled) edges were observed. The initiation for the 3 mm samples at higher stress is not clearly defined because there was no minimum on the compliance vs number of cycles curve.

1.5/4.5 mm Samples

On Fig. 5, the endurance limit is indicated by a hatched area as in Fig. 2. The mean compliance of the unfailed samples within the limits of the hatched area is 1.04 ±.04 and 1.08 ±.05 for the failed samples. These data agree with previous discussion about the effect of compliance but the statistical significance is more questionable in this latter case.

Influence of thickness

On Fig. 7, the curves of Fig. 2 to 5 are superimposed along with other data taken from the literature. The three curves labeled "PLAIN" are for smooth specimens of 301L MT at R = -1 as provided by three manufacturers of the alloy. The curves labeled 2/2 from another reference (Hamel, 1987) correspond to non-load carrying spot welded joints of 2 mm thick SAE 950A HSLA steels. The curve labeled 1/1 from Defourny (1981, 1985) are for 1 mm thick non-load carrying samples of E380 HSLA steel tested at a load ratio R = .11.

Although there is a large scatter band for the endurance limit of the 1.5/1.5 and 1.5/4.5, the figure shows that the endurance limit and the high-cycle endurance decreases with the thickness. The 3/3 curve is within the scatter band of the 1.5/1.5 curve but its fatigue endurance was clearly inferior in the high-cycle region (10^5-10^6 cycles). The 4.5/4.5 specimens clearly had the lowest endurance. In every case, the fatigue limit is lower than the plain specimens[1]. This is the most important result of this investigation. The

[1] Some might argue that the plain specimens were tested at R = -1 rather than 0. This effect will be discussed later.

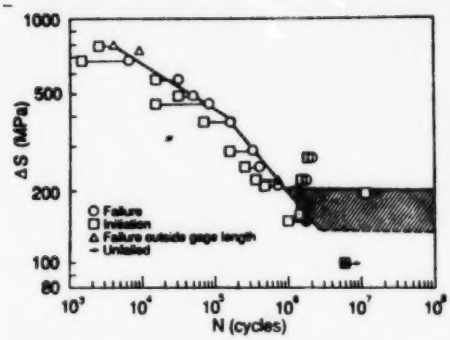

Fig. 2 SN curve for 1.5/1.5 specimens of 301L MT. Closed symbols designate samples from a different batch.

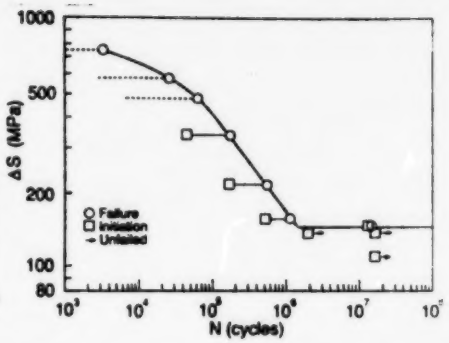

Fig. 3 SN curve for 3/3 specimens of 301L MT.

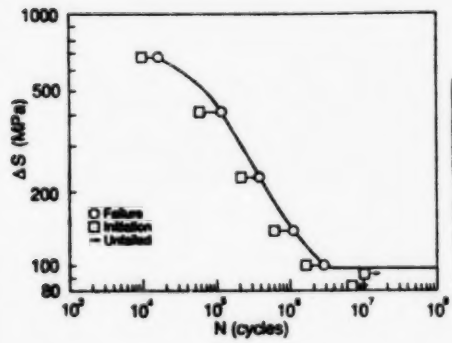

Fig. 4 SN curve for 4.5/4.5 specimens of 301L MT.

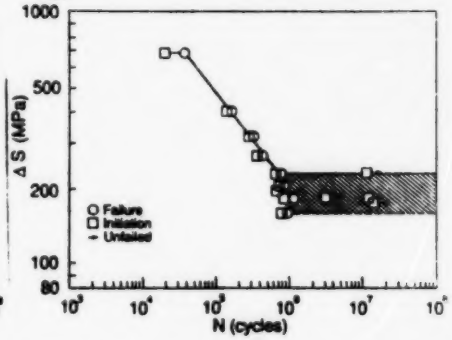

Fig. 5 SN curve for 1.5/4.5 specimens of 301L MT.

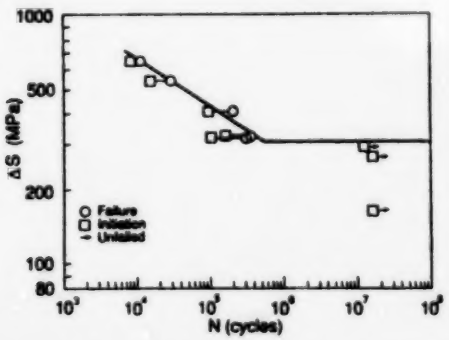

Fig. 6 SN curve for 301L MT samples with central drilled hole

presence of a non-load carrying attachement significantly reduces the fatigue endurance and the effect increases with the thickness of the attachement. In the case of 4.5/4.5 specimens, the fatigue limit is as low as about 10% of the static strength of 951 MPa.

The effect of thickness on the fatigue endurance of non-load carrying spot welded joints, agrees with a more general observation (Gurney, 1979) that the fatigue endurance decreases with thickness in welded structures. This can be interpreted with the fracture mechanics approach. For a given stress, a crack in a piece of the same proportions but of larger dimensions will have a higher stress intensity factor. The geometry of the two sheets and the nugget of a spot welded joint form a crack-like defect loaded in mode II. For a given geometry and stress, the stress intensity factor increases with the thickness.

Different thickness. The behaviour of the 1.5/4.5 specimens is very similar to the 1.5/1.5 and different from the 4.5/4.5. This clearly indicates that the stress (not the load) in the base plate and the thickness of the attachment are the controlling factors. The thickness of the base plate has a negligible influence. However, the endurance limit scatter band is slightly higher for the 1.5/4.5 specimens than for the 1.5/1.5 one. This might be attributed to a small influence of the relative thickness of the attachment and the base

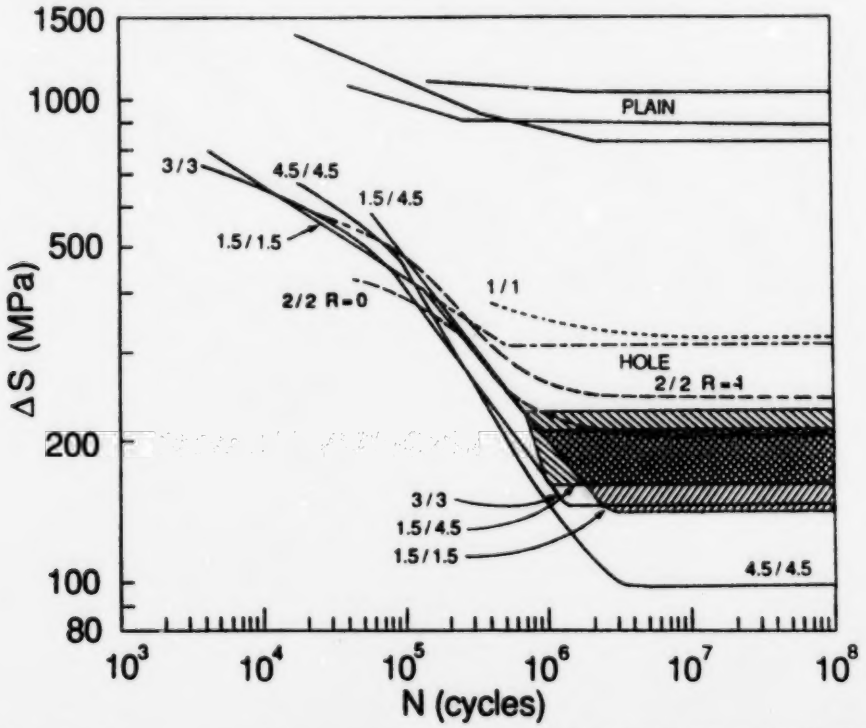

Fig. 7 Summary of all ΔS vs N curves for 301L MT (plain holed and spot welded) and other data for non-load carrying spot welded joints.

plate. It could also be attributed to the fact that the measured spot diameter of the 1.5/4.5 specimens (7.0 mm) was slightly smaller than for the 1.5/1.5 specimens (7.6 mm). When comparing Fig. 2 and 5, it appears that the propagation phase is longer for the 1.5/1.5 specimens than for the 1.5/4.5 specimens. It has to be remembered that the method used to determine the "initiation" includes the phase to propagate the thumbnail crack to the opposite face of the sheet. That phase is of course longer for thicker plate. However, at that moment, the crack is larger for the thicker plate, has a higher stress intensity factor and will propagate faster to the final failure.

Spot diameter. In this study, the spot diameter was varied with the thickness to be the same as in actual structures based on the actually accepted standards. No test was done to investigate seperately the effect of the plate thickness and of the nugget diameter. It is believed that the endurance depends on the joint stiffness which is a combined function on these two factors (thickness and nugget diameter).

Influence of Materials

On Fig. 7, curves from the literature (Defourny, 1981, 1985) for other non-load carrying joints from different material (HSLA steel) are also indicated. The endurance limit of the 1/1 specimens is the highest of all the data. For the 2/2, R = 0 curve, it is within the scatter band of the 1.5/1.5 and 1.5/4.5 results. These data agree with our previous discussion about the thickness effect and suggest the alloy has a less important effect than the thickness on the endurance limit. The tests of Sperle (1984) on 1.2 mm thick sheets showed a negligeable influence on the non-load carrying attachments. This aggres with the conclusion that the influence decreases with the thinner sheets. The reason why the influence was smaller for the 1.2 thick sheets of Sperle (1984) than for the 1 mm thick sheets of Defourny (1981, 1985) is not known. Some secondary factors not considered in this study (like the alloy or the specimen geometry) might be the explanation.

Influence of Load Ratio, R

The two dashed curves for the 2/2 samples indicate that the influence of R on the endurance limit is relatively small. This can be attributed to the fact that most of the life is spent in the short crack growth regime where the influence of R is small (Verreman,1986). For the same reason, it seems justified to compare the endurance limit of plain specimens at R = -1 and welded joints at R = 0 in terms of stress range (ΔS) rather than maximum stress even if a small influence of R is known to exist.

The situation is different at high stress where all the curves tend to their respective static strength. In this low-cycle regime, it is better to plot the curves in terms of S_{max} as shown on Fig. 8. Of course, the curves at R = 0, occupy the same positions than on Fig. 7 and only the curves for R ≠ 0 are moved. All the curves tend to their respective static strength values of 920 MPa for 301L, 480 MPa for the 2/2 HSLA specimens and 500 MPa for the 1/1 HSLA specimens.

All the curves for 301L MT all well grouped for less than 10^5 cycles. The reason why the curves for the 4.5 mm thick sheets are higher is not known exactly, and could simply be attributed to data scatter. As shown in Table 1, the yield and tensile strenghts are slightly higher than for the thinner sheets but the small difference is not believed to be large enough to explain the

difference in fatigue life.

It is also significant that the order of the curves in the high-cycle regime is not changed. The conclusions stated earlier about the effect of non-load carrying spot welded joints are not affected and cannot be attributed to the fact that the data available for plain specimens were at R = -1. Moreover, as mentioned earlier, the fact that the two curves for the 2/2 samples are much closer on the ΔS than on the S_{max} (Fig. 8) curve justifies the comparison on the ΔS curve in high-cycle fatigue. Fatigue data were not obtained at $N < 10^4$ cycles for the 2/2 specimens but it is known that these curves will tend to the static strength of 480 MPa (960 for R = -1 on ΔS scale) at N = 1. Consequently the two curves will move off on the ΔS curve and will come closer on the S_{max} curve.

It can be observed that the curve for the samples with a hole, crosses the curves for non-load carrying spot welded samples at intermediate lives (10^4-10^5 cycles). This behaviour can be qualitatively explained by the model developed by Dowling (1979) and Socie (1984). The samples with a hole behave like a blunt notch. For such a notch, crack growth consumes the majority of the fatigue life at intermediate stress and crack nucleation dominates the endurance limit behaviour. On the other hand, the spot welded samples behave like sharply notched members. In this case short crack propagation consumes the majority of the fatigue life at all stress levels. The endurance limit is controlled by the behaviour of short non-propagating cracks.

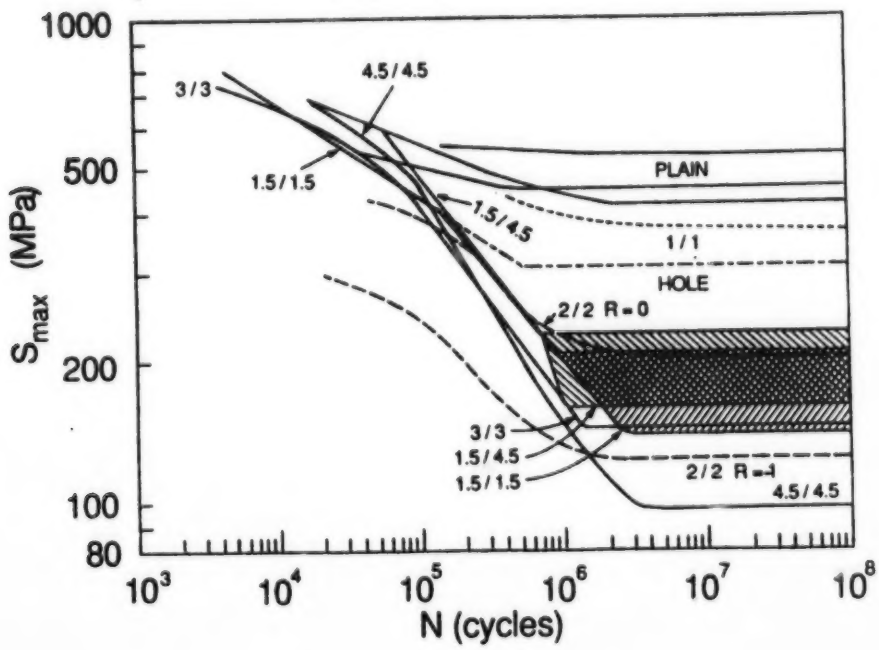

Fig. 8 Summary of all curves of Fig. 7 plotted on a S_{max} vs N graph

CONCLUSION

The following conclusions can be stated about the behaviour of non-load carrying spot welded joints.

1) The presence of a non-load carrying spot welded joint significantly reduces the fatigue limit of the base sheet to which it is attached

2) This life reducing effect significantly increases with the thickness of the attachment

3) The controlling factors are the stress in the base sheet and the rigidity of the attachment (determined by thickness of the attachment, size and quality of the spot). The thickness of the base sheet seems to have a negligible effect

4) The steel composition and mechanical properties seems to have a negligible effect at low stress

5) The fatigue endurance reducing effect of non-load carrying spot welded joints is eliminated at high stresses. The mechanical properties of the steel are important at high stresses

6) The fatigue endurance is better described by the ΔS parameter at low stress and by the S_{max} parameter at high stress.

7) The fatigue endurance is improved by the presence of oil between the sheets

From a practical point of view, the first two conclusions are obviously the most significant. Non-load or low-load carrying spot welded joints should be carefully considered in fatigue design especially for thick sheets. Not only the load carried by a spot but also the stress existing in the sheets should be considered. Additional research is however needed to quantify the possible synergetic effect of the stress level of the base sheet and the load transmitted by the spot.

ACKNOWLEDGEMENT

The authors would like to thank R. Lavallée who carried on the tests. We also thank Bombardier Inc. who manufactured the spot welded samples. Helpful discussions with J. Janssen of Bombardier Inc. were also greatly appreciated.

REFERENCES

Davidson, J.A. (1983a). A review of the fatigue properties of spot-welded sheet steels. 1983 SAE Int. Congress and Exposition, Detroit, Mich., Technical Paper 830033.

Davidson, J.A. and Imhof, J.E., Jr. (1983b). A fracture-mechanics and system-stiffness approach to fatigue performance of spot-welded sheet steels, SAE Int. Congress and Expositions, Detroit, Mich., Technical Paper 830034.

Davidson, J.A. (1983c). Design related methodology to determine the fatigue life and related failure mode of spot welded sheet steels. 1983 Int. Conf. on Technology and Applications of HSLA Steels, Philadelphia, Penn., ASM Paper 8306-022.

Davidson, J.A. and Imhof, J.E., Jr. (1984). The effect of tensile strength on the fatigue life of spot-welded sheet steels. 1984 SAE Int. Congress and Exposition, Detroit, Mich., Technical Paper 840110.

Defourny, J., d'Haeyer, R. and Bragard, A. (1981). Experience of CRM in the resistance spot welding of high strength steel sheet. Proceedings of Welding of High Strength Steel Symposium, Coventry.

Defourny, J. and Bragard, A. (1985). Welding in the World, 23, 5/6, 100-122.

Dowling, N.E. (1979). Fracture Mechanics, ASTM STP 677, Smith, C.W., ed. ASTM, 247-273.

Gurney, T.R. (1979). Fatigue of Welded Structures, 2nd ed., Cambridge University Press, 66 and 123.

Hamel, F.G. and Masounave, J. (1987). The fatigue behaviour of non-load carrying spot welded joints. Submitted to Int. J. Fatigue.

Iwasaki, T. Tanaka J., Kabasawa, M. and Nagae, M. (1983). Welding Research Abroad, XXIX, 3, 38-47.

Orts, D.H. (1981) Fatigue strength of spot welded joints in HSLA steel", 1981 SAE Int. Congress and Exposition, Detroit, Mich., Technical Paper 810355.

Overbeeke, J.L. and Draisma, J. (1974). Metal Construction, 6, 213-219.

Pollard, B. (1974). Welding Research Supplement, 53, 8, 343s-350s.

Pook, L.P. (1975). Int. J. Fract., 11, 173-176.

Rivett, R.M. (1983). Assessment of resistance spot welds in low carbon and high strength steel sheet, 1983 SAE Int. Congress and Exposition, Detroit, Mich., Technical Paper 830126.

Socie, D.F., Dowling, N.E. and Kurath, P. (1984). Fracture Mechanics: Fifteenth Symposium, ASTM STP 833, Sanford, R.J. ed., ASTM, 284-299.

Sperle, J.O. (1984). Metal Construction, 16, 11, 678-679.

Verreman Y., Bailon J.-P. and Masounave, J. (1986). Fatigue short crack propagation and plasticity induced crack closure at the toe of a fillet welded joint", The Behaviour of Short Fatigue Cracks, EGF Pub. 1, Miller, K.J. and De LosRios, E.R., Mechanical Engineering Publications, London, 387-404.

Wang, P.C., Corten, H.T. and Lawrence, F.V. (1985). A fatigue life prediction method for tensile-shear spot welds. 1985 SAE Int. Congress and Exposition, Detroit, Mich., Technical Paper 850370.